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ABSTRACT

Human linguistic ability depends, in part, on the gradual evolution of man's supralaryngeal vocal tract. The anatomic basis of human speech production is the result of a long evolutionary process in which the Darwinian process of natural selection acted to retain mutations. For auditory perception, the listener operates in terms of the acoustic pattern of the entire syllable according to the "motor theory of speech perception." According to the theory, human listeners perceive speech in terms of the constraints imposed by the speech-producing apparatus. It has recently been possible to reconstruct the supralaryngeal vocal tracts of extinct hominid species. Computer-implemented supralaryngeal vocal tract modelling indicates that these extinct species lacked the anatomic ability necessary to produce the range of sounds necessary for human speech. (Author/VM)

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On the Evolution of Human Language*

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ABSTRACT

Recent theoretical and experimental advances have demonstrated that the sounds of human speech make human language an effective medium of communication through a process of speech "encoding." The presence of sounds like the language universal vowels /a/, /u/, and /i/ makes this process possible. In the past five years we have shown that the anatomic basis of human speech is species-specific. We have recently been able to reconstruct the supralaryngeal vocal tracts of extinct hominid species. These reconstructions make use of the methods of comparative anatomy and skeletal similarities that exist between extinct fossils and living primates like newborn homo sapiens and the nonhuman primates. Computer-implemented supralaryngeal vocal tract modelling indicates that these extinct species lacked the anatomic ability that is necessary to produce the range of sounds that is necessary for human speech. Human linguistic ability depends, in part, on the gradual evolution of modern man's supralaryngeal vocal tract. Species like "classic" Neanderthal man undoubtedly had language, but their linguistic ability was markedly inferior to modern man's.

Human language is one of the defining characteristics that differentiate modern man from all other animals. The traditional view concerning the uniqueness of human linguistic ability is that it is based on man's mental processes (Lenneburg, 1967). In other words the "uniqueness" of human language is supposed to be entirely due to the properties of the human brain. The particular sounds that are employed in human language are therefore often viewed as an arbitrary, fortuitously determined set of cipher-like elements. Any other set of sounds or gestures supposedly would be just as useful at the communicative, i.e., the phonetic, level of human language.

The results of recent research have, however, challenged this view. The "motor theory" of speech perception that has been developed over the past fifteen years, in essence, states that speech signals are perceived in terms of the constraints that are imposed by the human vocal apparatus (Liberman et al., 1967). Other recent research, which I will attempt to summarize in this paper, indicates that the anatomic basis of human speech production is itself species-specific. This research is the product of a collaborative effort involving many skills. Edmund S. Crelin of the Yale University School of

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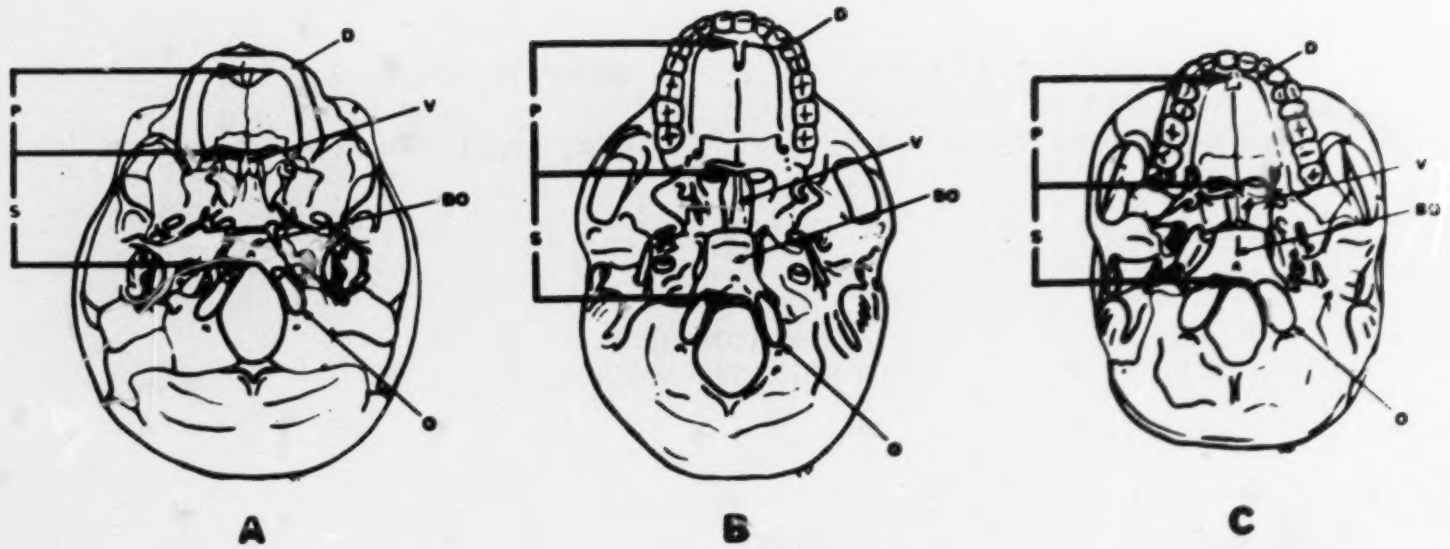
Medicine, Dennis H. Klatt of M.I.T., Peter Wolff of Harvard University, and my colleagues at the University of Connecticut and Haskins Laboratories have all been involved at one time or another. Our research indicates that the anatomic basis of human speech production is the result of a long evolutionary process in which the Darwinian process of natural selection acted to retain mutations that would enhance rapid communication through the medium of speech. The neural processes that are involved in the perception of speech and the unique species-specific aspects of the human supralaryngeal vocal tract furthermore appear to be interrelated in a positive way.

Vocal Tract Reconstruction

The most direct approach to this topic is to start with our most recent experimental technique, the reconstruction and functional modelling of the speech-producing anatomy of extinct fossil hominids. We have been able to reconstruct the evolution of the human supralaryngeal vocal tract by making use of the methods of comparative anatomy and skeletal similarities that exist between extinct fossil hominids and living primates (Lieberman and Crelin, 1971). In Figure 1 inferior views of the base of the skull are shown for newborn modern man, a reconstruction of the fossil La Chappelle-aux-Saints Neanderthal man, and an adult modern man. The detailed morphology of the base of the skull and mandible, which is similar in newborn modern man and Neanderthal man, forms the basis for the Neanderthal reconstruction. Some of the skull features that are similar in newborn modern man and Neanderthal man, but different from adult modern man, are as follows: (1) the skulls have a generally flattened out base; (2) they lack a chin; (3) the body of the mandible is 60 to 100 percent longer than the ramus; (4) the posterior border of the mandibular ramus is markedly slanted away from the vertical plane; (5) there is a more horizontal inclination of the mandibular foramen leading to the mandibular canal; (6) the pterygoid process of the sphenoid bone is relatively short and its lateral lamina is more inclined away from the vertical plane; (7) the styloid process is more inclined away from the vertical plane; (8) the dental arch of the maxilla is U-shaped instead of V-shaped; (9) the basilar part of the occipital bone between the foramen magnum and the sphenoid bone is only slightly inclined away from the horizontal toward the vertical plane; (10) the roof of the nasopharynx is a relatively shallow elongated arch; (11) the vomer bone is relatively short in its vertical height and its posterior border is inclined away from the vertical plane; (12) the vomer bone is relatively far removed from the junction of the sphenoid bone and the basilar side part of the occipital bone; (13) the occipital condyles are relatively small and elongated. These similarities are in accord with other skeletal features typical of Neanderthal fossils (Vlček, 1970), which may be seen in the course of the ontogenetic development of modern man. This, parenthetically, does not mean that Neanderthal man was a direct ancestral form of modern man since Neanderthal fossils exhibit specializations like brow ridges that never occur in the ontogenetic development of modern man. Modern man, furthermore, deviates quite drastically from Neanderthal man in the course of normal maturation from the newborn state.

In Figure 2 lateral views of the skull, vertebral column, and larynx of newborn and adult modern man and Neanderthal man are presented. The significance of the aforementioned skeletal features with regard to the supralaryngeal vocal tract can be seen in the high position of the larynx in newborn and in Neanderthal.

Inferior Views of Base of Skull



NEWBORN NEANDERTHAL ADULT MAN

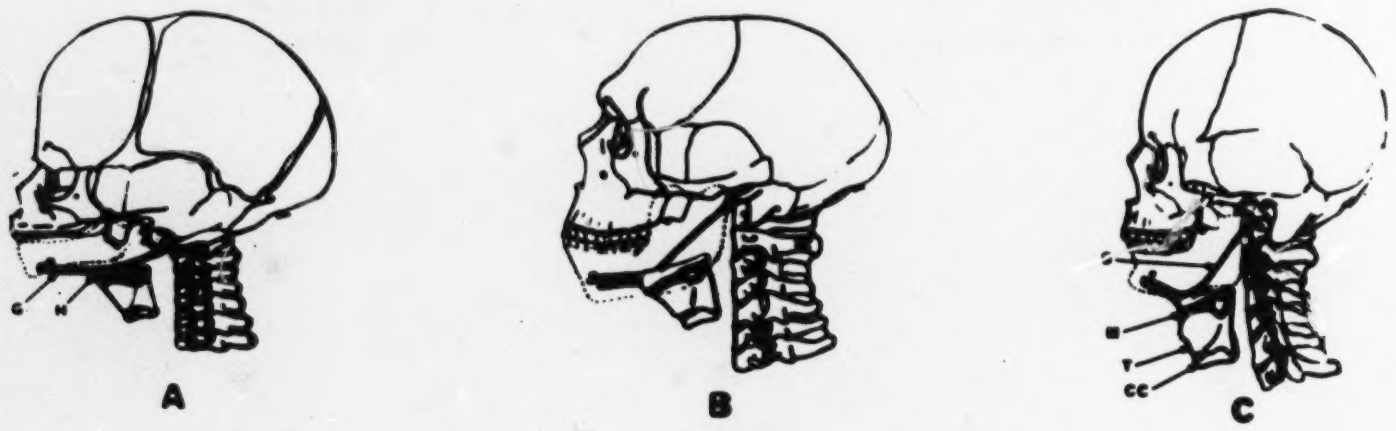
D - Dental Arch
P - Palate
S - Distance Between Palate and Foramen Magnum

V - Vomer Bone
BO - Basilar Part of Occipital
O - Occipital Condyle

(After Lieberman and Crelin, 1971.)

Fig. 1

Skull, Vertebral Column, and Larynx



NEWBORN | RECONSTRUCTION OF NEANDERTHAL | ADULT MAN

G - Geniohyoid Muscle
H - Hyoid Bone
S - Stylohyoid Ligament
M - Thyrohyoid Membrane
T - Thyroid Cartilage
CC - Cricoid Cartilage

Fig. 2 Note that the inclination of the styloid process away from the vertical plane in newborn and Neanderthal results in a corresponding inclination in the stylohyoid ligament. The intersection of the stylohyoid ligament and geniohyoid muscle with the hyoid bone of the larynx occurs at a higher position in newborn and Neanderthal. The high position of the larynx in the Neanderthal reconstruction follows, in part, from this intersection. (After Lieberman and Crelin, 1971.)

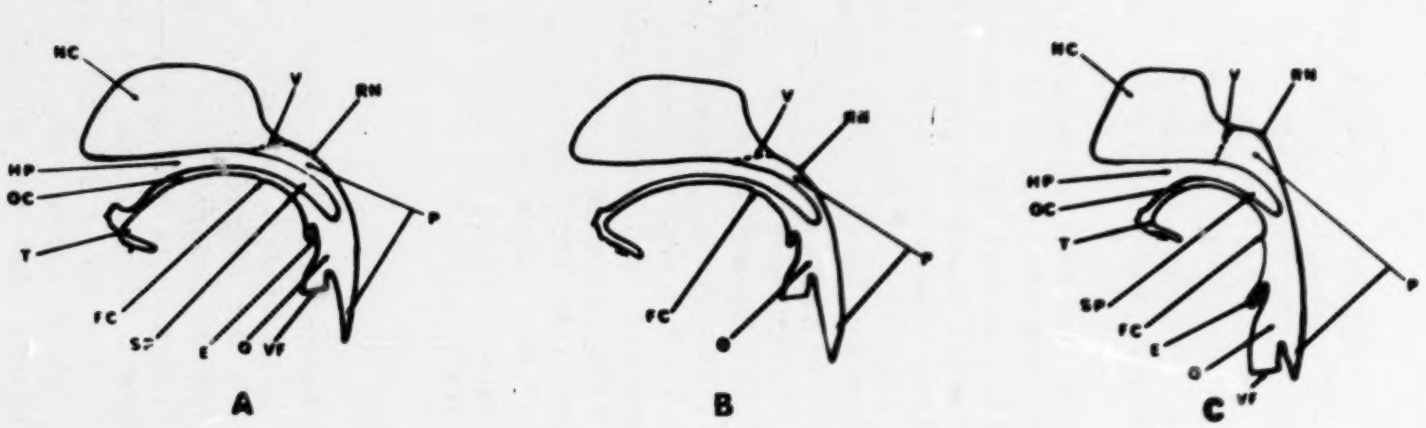
In Figure 3 the supralaryngeal air passages of newborn and adult man and the Neanderthal reconstruction are diagrammed so that they appear equal in size. Although the nasal and oral cavities of Neanderthal are actually larger than those of adult modern man, they are quite similar in shape to those of the newborn. The long "flattened out" base of the skull in newborn and Neanderthal is a concomitant skeletal correlate of a supralaryngeal vocal tract in which the entrance to the pharynx lies behind the entrance to the larynx. In the ontogenetic development of adult modern man the opening of the larynx into the pharynx shifts to a low position. In this shift the epiglottis becomes widely separated from the soft palate. The posterior part of the tongue, between the foramen cecum and the epiglottis, shifts from a horizontal resting position within the oral cavity to a vertical resting position, to form the anterior wall of the oral part of the pharynx (Figure 3C). In this shift the epiglottis becomes widely separated from the soft palate.

The uniqueness of the adult human supralaryngeal vocal tract rests in the fact that the pharynx and oral cavities are almost equal in length and are at right angles. No other animal has this "bent" supralaryngeal vocal tract in which the cross-sectional areas of the oral and pharyngeal cavities can be independently modified. The human vocal tract can, in effect, function as a "two tube" acoustic filter. In Figure 4 we have diagrammed the "bent" human supralaryngeal vocal tract in the production of the "extreme," "point" vowels /i/, /a/, and /u/. Note that the midpoint area function changes are both extreme and abrupt. Abrupt discontinuities can be formed at the midpoint "bend." In Figure 5 the nonhuman "straight" vocal tract which is typical of all living nonhuman primates (Lieberman, 1968; Lieberman et al., 1969, and Lieberman et al., in press), newborn humans (Lieberman et al., 1968), and Neanderthal man, is diagrammed as it approximates these vowels. All area function adjustments have to take place in the oral cavity in the nonhuman supralaryngeal vocal tract. Although midpoint constrictions obviously can be formed in the nonhuman vocal tract, they cannot be both extreme and abrupt. The elastic properties of the tongue prevent it from forming abrupt discontinuities at the midpoint of the oral cavity.

Vocal Tract Modelling

Human speech is essentially the product of a source, the larynx for vowels, and a supralaryngeal vocal tract transfer function. The supralaryngeal vocal tract in effect filters the source (Chiba and Kajiyama, 1958; Fant, 1960). The activity of the larynx determines the fundamental frequency of the vowel, whereas its formant frequencies are the resonant modes of the supralaryngeal vocal tract. The formant frequencies are determined by the area function of the supralaryngeal vocal tract. Man uses his articulators (the tongue, lips, mandible, pharyngeal constrictors, etc.) to modify dynamically in time the formant frequency patterns that the supralaryngeal vocal tract imposes on the speech signal. The phonetic inventory of a language is therefore limited by (1) the number of source function modifications that a speaker is capable of controlling during speech communication and (2) the number of formant frequency patterns available by changing the supralaryngeal area function through the dynamic manipulation of the articulators. We thus can assess the contribution of the supralaryngeal vocal tract to the phonetic abilities of a hominid, independent of the source characteristics. A computer-implemented model of a supralaryngeal vocal tract (Henke, 1966) can be used to determine the possible contribution of the vocal tract to the phonetic repertoire. We can conveniently

Supralaryngeal Air Passages



NC - Nasal Cavity
V - Vomer Bone
RN - Roof of Nasopharynx
P - Pharynx
HP - Hard Palate
SP - Soft Palate
OC - Oral Cavity
T - Tip of Tongue
FC - Foramen Cecum of Tongue
E - Epiglottis
O - Opening of Larynx into Pharynx
VF - Level of Vocal Folds

(After Lieberman and Crelin, 1971.)

Fig. 3

6

Schematic Diagram of the "Bent" Human Supralaryngeal Vocal Tract

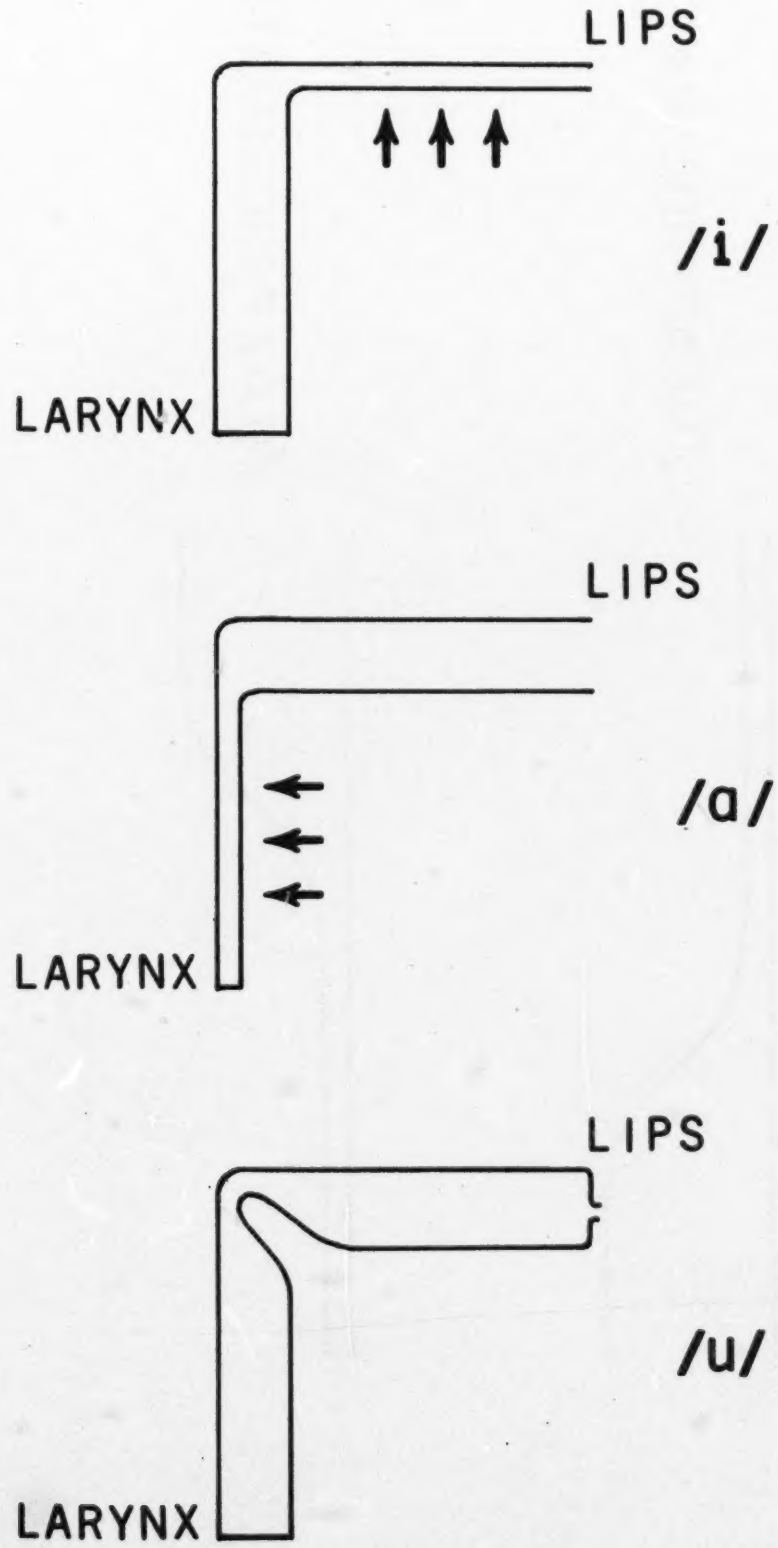


Fig. 4

Note that abrupt and extreme discontinuities in cross-sectional area can occur at the midpoint.

Schematic Diagram of the Straight, "Single Tube" Nonhuman Vocal Tract

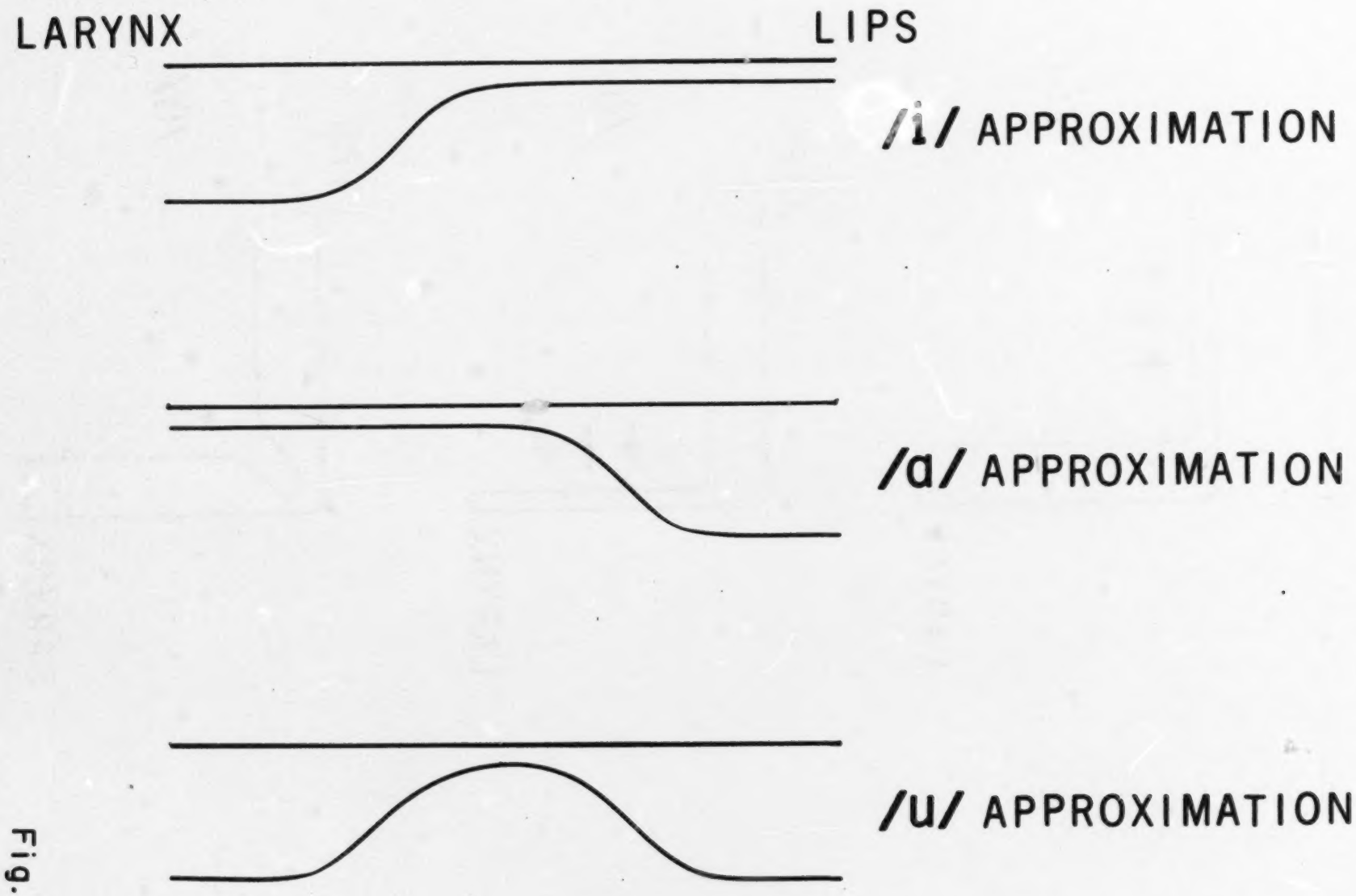


Fig. 5

Note that abrupt midpoint constrictions cannot be formed.

begin to determine whether a nonhuman supralaryngeal vocal tract can produce the range of sounds that occur in human language by exploring its vowel-producing ability. Consonantal vocal tract configurations can also be modelled. It is, however, reasonable to start with vowels since the production of consonants may also involve rapid, coordinated articulatory maneuvers and we can only speculate on the presence of this ability in fossil hominids.

In Figure 6 we have presented area functions of the supralaryngeal vocal tract of Neanderthal man that were modelled on the computer. These area functions were directed towards best approximating the human vowels /i/, /a/, and /u/. Our computer modelling (Lieberman and Crelin, 1971) was guided by the results of X-ray motion pictures of speech production, swallowing, and respiration in adult human (Haskins Laboratories, 1962; Perkell, 1969) and in newborn (Truby et al., 1965). This knowledge plus the known comparative anatomy of the living primates allowed a fairly "conservative" simulation of the vowel-producing ability of classic Neanderthal man. We perhaps allowed a greater vowel-producing range for Neanderthal man since we consistently generated area functions that were more human-like than ape-like whenever we were in doubt. Despite these compensations the Neanderthal vocal tract cannot produce /i/, /a/, or /u/.

In Figure 7 the formant frequency patterns calculated by the computed program for the numbered area functions of Figure 6 are plotted. The labelled loops are derived from the Peterson and Barney (1952) analysis of the vowels of American-English of 76 adult men, adult women, and children. Each loop encloses the data points that accounted for 90 percent of the samples in each vowel category. We have compared the formant frequencies of the simulated Neanderthal vocal tract with this comparatively large sample of human speakers since it shows that the speech deficiencies of the Neanderthal vocal tract are different in kind from the differences that characterize human speakers. Since all human speakers can inherently produce all the vowels of American-English, we have established that the Neanderthal phonetic repertoire is inherently limited. In some instances we generated area functions that would be human-like, even though we felt that we were forcing the articulatory limits of the reconstructed Neanderthal vocal tract (e.g., area functions 3, 9, and 13). However, even with these articulatory gymnastics the Neanderthal vocal tract could not produce the vowel range of American-English.

Functional Phonetic Limitations

There are some special considerations that follow from the absence of the vowels /i/, /a/, and /u/ from the Neanderthal phonetic repertoire. Phonetic analyses have shown that these "point" vowels are the limiting articulations of a vowel triangle that is almost language universal (Troubetzkoy, 1939). The special nature of /i/, /a/, and /u/ can be argued from theoretical grounds as well. Employing simplified and idealized area functions (similar to those sketched in Figure 4) Stevens (1969) has shown that these articulatory configurations (1) are acoustically stable for small changes in articulation and therefore require less precision in articulatory control than similar adjacent articulations and (2) contain a prominent acoustic feature, i.e., two formants that are in close proximity to form a distinct energy concentration.

The vowels /i/, /a/, and /u/ have another unique acoustical property. They are the only vowels in which an acoustic pattern can be related to a

Area Functions of the Supralaryngeal Vocal Tract of Neanderthal Reconstruction Modelled on Computer

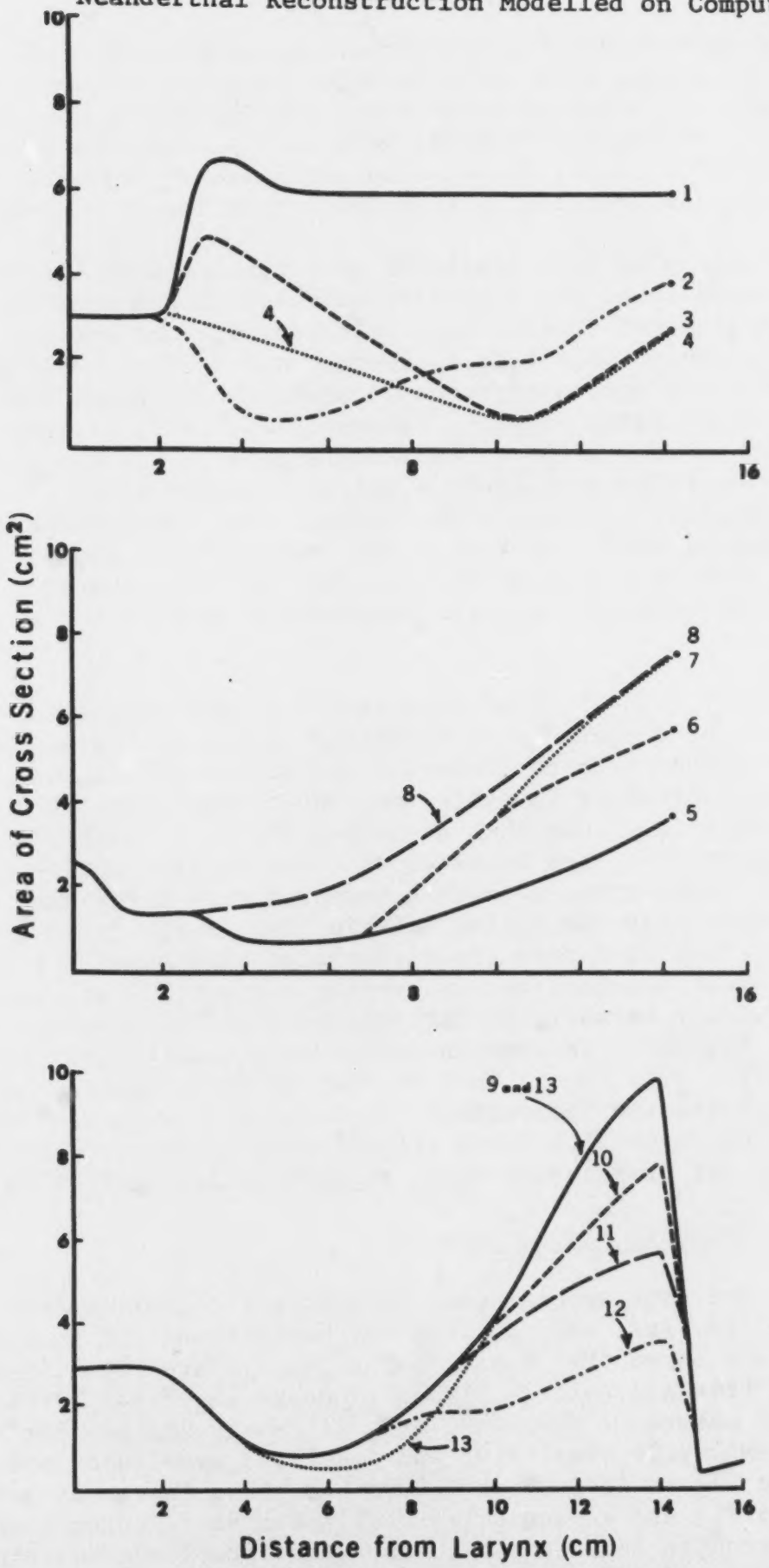
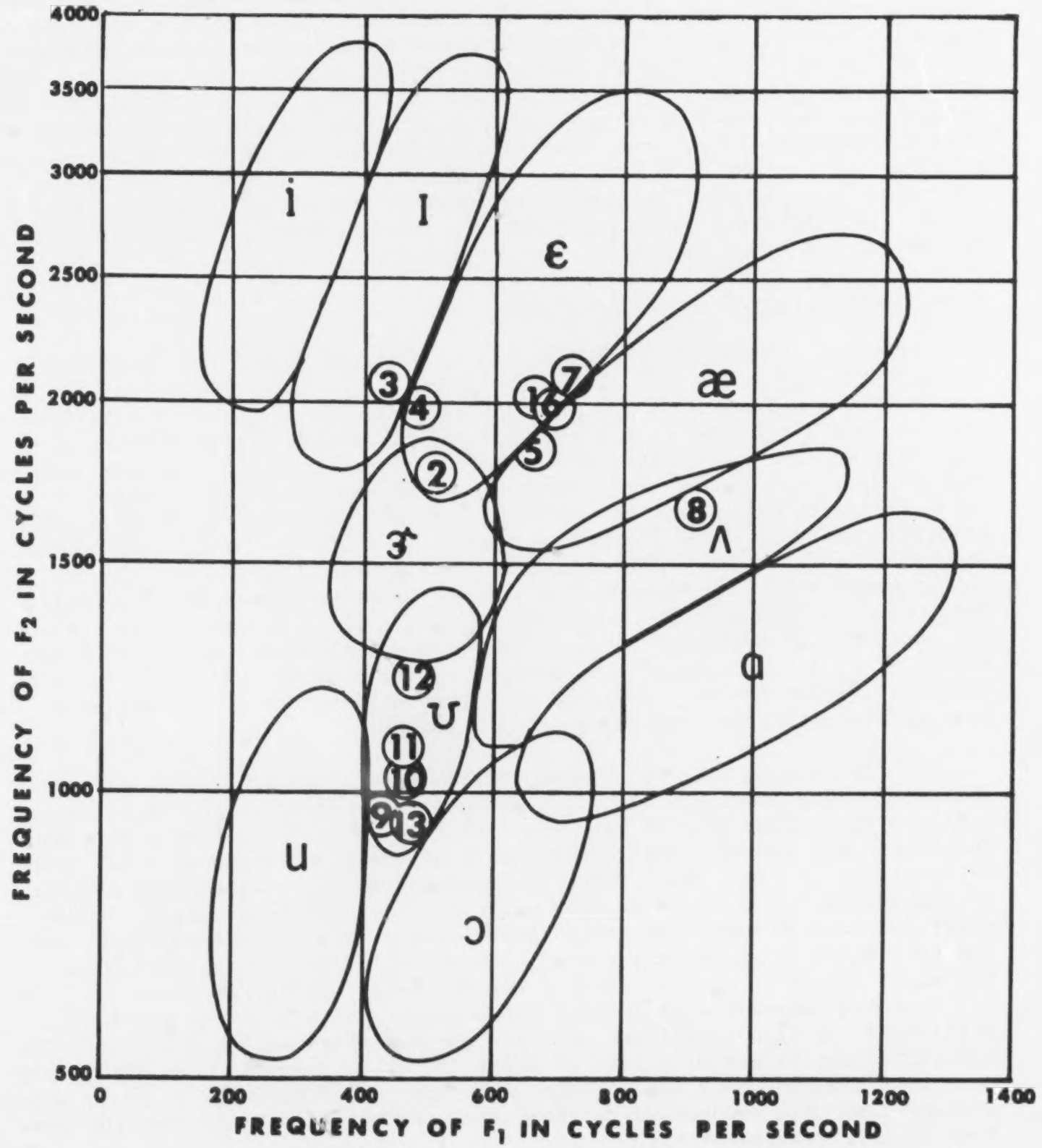


Fig. 6

The area function from 0 to 2 cm is derived from Fant (1960) and represents the distance from the vocal folds to the opening of the larynx into the pharynx. Curve 1 is the unperturbed tract. Curves 2, 3, and 4 represent functions directed towards a "best match" to the human vowel /i/. Curves 5-8 are functions directed towards a "best match" to /a/, while curves 9-13 are directed towards /u/. (After Lieberman and Crelin, 1971.)

Formant Frequencies Calculated by Computer Program for Neanderthal Reconstruction



The numbers refer to area functions in Figure 6. (After Lieberman and Crelin, 1971.)

Fig. 7

unique vocal tract area function. Other "central" vowels can be produced by means of several alternate area functions (Stevens and House, 1955). A human listener, when he hears a syllable that contains a token of /i/, /a/, and /u/, can calculate the size of the supralaryngeal vocal tract that was used to produce the syllable. The listener, in other words, can tell whether a speaker with a large or small vocal tract is speaking. This is not possible for other vowels since a speaker with a small tract can, for example, by increasing the degree of lip rounding, produce a token of /U/ that would be consistent with a larger vocal tract with less lip rounding. These uncertainties do not exist for /i/, /a/, and /u/ since the required discontinuities and constrictions in the supralaryngeal vocal tract area functions produce acoustic patterns that are beyond the range of compensatory maneuvers.

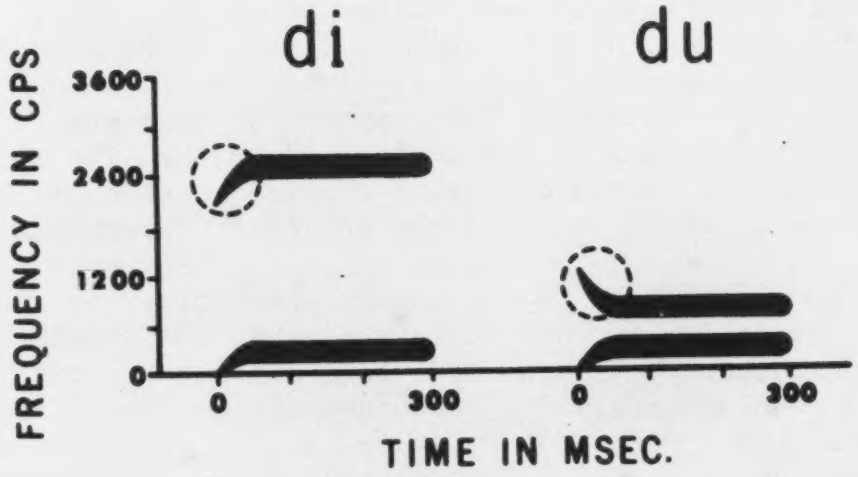
Speech Perception and Speech Anatomy

We noted, at the start of this paper, that the results of perceptual research have demonstrated that human listeners perceive speech in terms of the constraints imposed by the speech-producing apparatus. This mode of perception, which has been termed the "speech" or "motor" theory mode of perception makes the rapid rate of information transfer of human speech possible (Liberman, 1970). Human listeners can perceive as many as 30 phonetic segments per second in normal speech. This information rate far exceeds the temporal resolving power of the human auditory system. It is, for example, impossible even to count simple pulses at rates of 20 pulses per second. The pulses merge into a continuous tone. Human speech achieves its high information rate by means of an "encoding" process that is structured in terms of the anatomic and articulatory constraints of speech production. The motor theory of speech perception, in essence, explicates this process. The presence of vowels like /i/, /a/, and /u/ appears to be one of the anatomic factors that makes this encoding process possible.

In Figure 8 we have reproduced two simplified spectrographic patterns that will, when converted to sound, produce approximations to the syllables /di/ and /du/ (Liberman, 1970). The dark bands on these patterns represent the first- and second-formant frequencies of the supralaryngeal vocal tract as functions of time. Note that the formants rapidly move through a range of frequencies at the left of each pattern. These rapid movements, which occur in about 50 msec, are called transitions. The transition in the second formant, which is encircled, conveys the acoustic information that human listeners interpret as a token of a /d/ in the syllables /di/ and /du/. It is, however, impossible to isolate the acoustic pattern of /d/ in these syllables. If tape recordings of these two syllables are "sliced" with the electronic equivalent of a pair of scissors, it is impossible to find a segment that contains only /d/. There is no way to cut the tape so as to obtain a piece that will produce /d/ without also producing the next vowel or some reduced approximation to it.

Note that the encircled transitions are different for the two syllables. If these encircled transitions are isolated, listeners report that they hear either an upgoing or a falling frequency modulation. In context, with the acoustic correlates of the entire syllable, these transitions cause listeners to hear an "identical" sounding /d/ in both syllables. How does a human listener effect this perceptual response?

Simplified Spectrographic Patterns
Sufficient to Produce the Syllables /di/ and /du/



The circles enclose the second formant frequency transitions.
(After Liberman, 1970.)

Fig. 8

We have noted the formant frequency patterns of speech reflect the resonances of the supralaryngeal vocal tract. The formant patterns that define the syllable /di/ in Figure 8 thus reflect the changing resonant pattern of the supralaryngeal vocal tract as the speaker moves his articulators from the occlusion of the tongue tip against the palate that is involved in the production of /d/ to the vocal tract configuration of the /i/. A different acoustic pattern defines the /d/ in the syllable /du/. The resonances of the vocal tract are similar as the speaker forms the initial occlusion of the /d/ in both syllables; however, the resonances of the vocal tract are quite different for the final configurations of the vocal tract for /i/ and /u/. The formant patterns that convey the /d/ in both syllables are thus quite different since they involve transitions from the same starting point to different end points. Human listeners "hear" an identical initial /d/ segment in both of these signals because they "decode" the acoustic pattern in terms of the articulatory gestures and the anatomical apparatus that is involved in the production of speech. The listener in this process, which has been termed the "motor theory of speech perception" (Liberman et al., 1967), operates in terms of the acoustic pattern of the entire syllable. The acoustic cues for the individual "phonetic segments" are fused into a syllabic pattern. The high rate of information transfer of human speech is thus due to the transmission of acoustic information in syllable-sized units. The phonetic elements of each syllable are "encoded" into a single acoustic pattern which is then "decoded" by the listener to yield the phonetic representation.

In order for the process of "motor theory perception" to work the listener must be able to determine the absolute size of the speaker's vocal tract. Similar articulatory gestures will have different acoustic correlates in different-sized vocal tracts. The frequency of the first formant of /a/, for example, varies from 730 to 1030 Hz in the data of Peterson and Barney (1952) for adult men and children. The frequencies of the resonances that occur for various consonants likewise are a function of the size of the speaker's vocal tract. The resonant pattern that is the correlate of the consonant /g/ for a speaker with a large vocal tract may overlap with the resonant pattern of the consonant /d/ for a speaker with a small vocal tract (Rand, 1971). The listener therefore must be able to deduce the size of the speaker's vocal tract before he can assign an acoustic signal to the correct consonantal or vocalic class.

There are a number of ways in which a human listener can infer the size of a speaker's supralaryngeal vocal tract. He can, for example, note the fundamental frequency of phonation. Children, who have smaller vocal tracts, usually have higher fundamental frequencies than adult men or adult women. Adult men, however, have disproportionately lower fundamental frequencies than adult women (Peterson and Barney, 1952), so fundamental frequency is not an infallible cue to vocal tract size. Perceptual experiments (Ladefoged and Broadbent, 1957) have shown that human listeners can make use of the formant frequency range of a short passage of speech to arrive at an estimate of the size of a speaker's vocal tract. Recent experiments, however, show that human listeners do not have to defer their "motor theory" decoding of speech until they hear a two- or three-second interval of speech. Instead, they use the vocalic information encoded in a syllable to decode the syllable (Darwin, in press; Rand, 1971). This may appear to be paradoxical, but it is not. The listener makes use of the formant frequencies and fundamental

frequency of the syllable's vowel to assess the size of the vocal tract that produced the syllable. We have noted throughout this paper that the vowels /a/, /i/, and /u/ have a unique acoustical property. The formant frequency pattern for these vowels can always be related to a unique vocal tract size and shape. A listener, when he hears one of these vowels, can thus instantly determine the size of the speaker's vocal tract. The vowels /a/, /i/, and /u/ (and the glides /y/ and /w/) thereby serve as acoustic calibration signals in human speech.

The absence of a human-like pharyngeal region in apes, newborn man, and Neanderthal man is quite reasonable. The only function that the human supralaryngeal vocal tract is better adapted to is speech production, in particular the production of vowels like /a/, /i/, and /u/. The human supralaryngeal vocal tract is otherwise less well adapted for the primary vegetative functions of respiration, chewing, and swallowing (Lieberman et al., 1971; Crelin et al., forthcoming). This suggests that the evolution of the human vocal tract which allows vowels like /a/, /i/, and /u/ to be produced and the universal occurrence of these vowels in human languages reflect a parallel development of the neural and anatomic abilities that are necessary for language. This parallel development would be consistent with the evolution of other human abilities. The ability to use tools depends, for example, both on upright posture and an opposable thumb, and on neural ability.

Neanderthal man lacked the vocal tract that is necessary to produce the human "vocal tract size-calibrating" vowels /a/, /i/, and /u/. This suggests that the speech of Neanderthal man did not make use of syllabic encoding. While communication is obviously possible without syllabic encoding, studies of alternate methods of communication in modern man show, as we noted before, that the rate at which information can be transferred is about one-tenth that of normal human speech.

It is imperative to note that classic Neanderthal man, as typified by fossils whose skull bases are similar to the La Chapelle-aux-Saints, La Ferrasie, La Quina, Pech-de-L'Azé, and Monte Circeo fossil hominids (as well as many others), probably does not represent the mainstream of human evolution. Although Neanderthal man and modern man probably had a common ancestor, Neanderthal represents a divergent species (Boule and Vallois, 1957; Vlček, 1970; Lieberman and Crelin, 1971). In Figure 9 we have photographed a casting of a reconstruction of the fossil Steinheim calvarium [illegible] the mandible of the La Chapelle-aux-Saints fossil. The mandible of the Steinheim fossil hominid never was found. Note that the La Chapelle-aux-Saints mandible is too long. In Figure 10 the Steinheim fossil has been fitted with a mandible from a normal adult human, which best "fits" the Steinheim fossil. We are in the process of reconstructing the supralaryngeal vocal tract of the Steinheim fossil (Crelin et al., forthcoming). It is quite likely that this fossil, which is approximately 300,000 years old, had the vocal tract anatomy that is necessary for human speech. The evolution of the anatomical basis for human speech thus would not appear to be the result of abrupt, recent change in the morphology of the skull and soft tissue of the vocal tract. We have noted a number of fossil forms that appear to represent intermediate stages in the evolution of the vocal tract. Recent fossil discoveries indicate that the evolution of the human vocal tract may have started at least 2.6 million years ago. It, therefore, is not surprising to find that the neural aspects of

Reconstructed Steinheim Clavarium with Neanderthaloid Mandible

Note that the Neanderthal mandible is too large. (After Crelin et al., forthcoming.)

Fig. 9

Reconstructed Steinheim Clavarium with a Modern Human Mandible

This represents the best "fit." (After Crelin et al., forthcoming.)

Fig. 10

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speech perception are matched to the anatomical aspects of speech production. Nor should we be surprised to note that "naturalness" constraints relate the phonetic and phonologic levels of grammar (Jakobson et al., 1952; Postal, 1968; Chomsky and Halle, 1969).

Sir Arthur Keith many years ago speculated on the antiquity of man. We now know that hominid evolution can be traced back at least 3 million years. The evolution of phonetic ability appears to have been an integral part of this evolutionary process. It may have its origins at the very beginnings of hominid evolution.

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